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Nondestructive sensing of bulk density and moisture content in shelled peanuts from microwave permittivity measurements

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Abstract

Dielectric-based methods were used to determine nondestructively and simultaneously bulk density and moisture content in shelled peanuts from measurement of their relative complex permittivity at microwave frequencies (7–12 GHz) and 24 °C. The first method is based on direct relationships between the two components of the relative complex permittivity (dielectric constant and dielectric loss factor) and the bulk density and moisture content. The second method allows bulk density determination without knowledge of moisture content and temperature of shelled peanut samples from a complex-plane representation of the relative complex permittivity. Finally, moisture content in shelled peanuts is determined independent of bulk density changes with the use of density-independent permittivity functions. Statistical analysis provided bulk density and moisture content calibration equations at several microwave frequencies along with corresponding standard errors of calibration over wide ranges of bulk density and moisture content.

Keywords: Nondestructive; Shelled peanuts; Bulk density; Moisture content; Complex permittivity; Microwave; Free space

1. Introduction

Peanuts and peanut-based products constitute an important group of food products available in the market place. Modern farming, handling and processing of peanuts require rapid testing methods for quality control assessment. Among the peanut properties that can be used for this purpose are bulk density and moisture content. Measurement of both parameters can also provide the mass of water per unit volume and the mass of dry matter per unit volume. One of the most useful applications of real-time sensing is to monitor moisture content during the process of peanut drying.

At harvest, peanuts generally have moisture contents between 15% and 20%, and they must be dried to less than 10.5% for sale or storage. Standard oven-drying techniques for moisture testing require drying several samples for several hours, which is both tedious and time consuming. Therefore, electrical moisture meters, calibrated against oven tests, are used for these measurements. Indirect methods such as RF impedance measurements (Kandala & Nelson, 1990) and microwave resonant cavity measurements (Kraszewski & Nelson, 1993) have been used for determining moisture content in a single peanut kernel.

The essence of microwave sensing relies on the wave/material interaction, which is characterized by the relative complex permittivity, and, for water-containing materials in particular, on the fact that the dielectric

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properties of water are much higher than those of dry matter. Also, the microwave frequency range is often selected for moisture sensing applications (Kent & Meyer, 1982; Meyer & Schilz, 1980; Meyer & Schilz, 1981) because the effect of ionic conduction is minimum and this range is above any relaxation processes that may alter the monotonic character of the relationship between the relative complex permittivity and moisture content. In this respect, dielectric-based methods are sensitive to water in all of its forms (bound and free) inside the material.

The method proposed in this paper provides simultaneously bulk density and moisture content in a bulk sample of shelled peanuts from measurement of the relative complex permittivity at microwave frequencies.

The relative complex permittivity ε, which will be referred to as the complex permittivity throughout the paper, is an intrinsic electrical property of the material that describes the electric field/material interaction. It is usually written in complex form as $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part, ε', or dielectric constant, characterizes the ability of a material to store the electric-field energy, and the imaginary part, ε'', the dielectric loss factor, reflects the ability of a material to dissipate electric energy in the form of heat. Because of its intrinsic nature, the complex permittivity is related to all variables describing the physical state of the system. These include for a sample of shelled peanuts, the bulk density, water content, and temperature. Therefore, finding explicit relationships between the two components of the complex permittivity and these physical properties provides a means for their determination instantaneously and nondestructively from measurement of the complex permittivity.

Several techniques can be used for complex permittivity measurement (Bussey, 1967; Von Hippel, 1954). Free-space techniques have the advantage of not requiring any contact between the measuring device and the sample. In this study, the complex permittivity is determined from measurement of the scattering transmission coefficient in free space over a broad microwave frequency range at room temperature. Dielectric-based methods can be used to determine simultaneously and nondestructively the bulk density ρ, and moisture content, M, of granular materials (Trabelsi, Kraszewski, & Nelson, 1999a). These methods range from direct relationships between the dielectric properties and ρ and M to the relationships between empirically-defined permittivity-based functions and physical characteristic of the medium (Kraszewski, Trabelsi, & Nelson, 1998; Trabelsi & Nelson, 1998).

Three methods were used for relating the complex permittivity of shelled peanuts to their moisture content and bulk density. The first method consisted of establishing direct relationships between the two components of the measured complex permittivity and ρ and M. With a system of two equations and two unknowns, analytical expressions for ρ and M in terms of ε' and ε'' were obtained. In the second method, the complex-plane representation of the dielectric properties divided by density was used to determine bulk density without knowledge of moisture content and temperature of shelled peanut samples (Trabelsi, Kraszewski, & Nelson, 1998). Finally, two of the most effective permittivity-based density-independent functions (Trabelsi & Nelson, 1998) for moisture determination were used to predict moisture content in shelled peanuts from measurements of the complex permittivity. Bulk density and moisture content calibration equations resulting from the different methods are given along with the standard error of calibration for each entity between 7 and 12 GHz at room temperature.

2. Materials and methods

2.1. Sample preparation and physical characteristics

The shelled peanut sample consisted of 7 kg of Runner type peanuts, cv. Georgia Green. Microwave measurements were performed on a sample with relatively low moisture content. Afterward, the sample moisture content was increased gradually in increments of about 1% until the higher end of the desired moisture range was reached. The sample moisture content was increased by spraying a fine mist of distilled water and stirring the peanut kernels to distribute the water evenly throughout the sample. For each moisture level, after the desired amount of water was added, the sample was placed in a sealed plastic bag and stored for at least 72 h at 4 °C to equilibrate. Before microwave measurements were taken, the sample was allowed to equilibrate to room temperature for 24 h.

After each microwave measurement sequence, three samples of shelled peanuts, 15 g each, were taken for moisture content testing according to the specifications of the ASAE standards (ASAE, 2002). The samples were oven-dried for 6 h at a temperature of 130 °C. Moisture content was calculated on the wet basis:

$$M(\%) = \frac{m_w}{m_w + m_d} 100 = \frac{m_w/V}{\rho} 100 \quad (1)$$

where m_w is the mass of water, m_d is the dry mass, V is the volume of the material and ρ is the bulk density. M is expressed in percent.

For each sample, ρ was determined by weighing the sample and then dividing the weight of the sample by the volume of the sample holder. In general, ρ is expressed in g/cm^3 or kg/m^3 as follows:

$$\rho = \frac{m_w + m_d}{V} \quad (2)$$

Another physical characteristic of the sample is its temperature. Temperature of each sample was measured after the microwave measurements were carried out with a digital thermocouple thermometer. In this study, moisture content ranged from 6.6% to 17.2%, bulk density ranged from 0.6 g/cm^3 to 0.73 g/cm^3, and temperature was about 24 °C. It is assumed that all three physical properties ρ, M and T remain constant and uniform throughout the sample.

2.2. Shelled peanuts permittivity measurements in free space

Dielectric properties of shelled peanuts were determined from measurement in free space of the scattering transmission coefficient, S_{21}. For each sample, a Styrofoam [1] container filled with peanut kernels was placed between two antennas facing each other and the modulus, $|S_{21}|$, and phase, φ, were measured. The measurement setup shown in Fig. 1 consists of a Hewlett Packard 8510C vector network analyzer (VNA), a computer, two high quality coaxial cables with APC-7 connectors at their terminations, two linearly polarized, ultrabroadband (2–26 GHz) horn/lens antennas (BAE SYSTEMS model AHO-2077-N), a Styrofoam sample holder, and four sheets of radiation-absorbing material, ECCOSORB AN-79, which isolated the sample from the surroundings. The measurements were conducted in a room where the relative humidity and temperature were controlled. The relative humidity was about 45% and the temperature was about 24 °C. In general, environmental conditions have no effect on microwave measurements (Kraszewski, 1991). For accurate determination of the complex permittivity, measurements were performed on samples of thickness that provided at least 10-dB one-way attenuation and measurements that remained within the dynamic range of the VNA. To accomplish this, Styrofoam spacers fitted inside the sample holder allowed different thicknesses of the sample to be tested to determine the best attenuation range for a given moisture level. Once the thickness was selected, the sample holder filled with the shelled peanuts was placed between two horn/lens antennas. These antennas collimated the electromagnetic energy in a narrow beam, which allowed the far-field condition to be fulfilled at a short distance from the transmitter, permitted the size of the sample to remain reasonable, and minimized edge diffraction. Also, time-domain gating was applied to the traces of $|S_{21}|$ and φ to filter out undesirable effects. For each sample, measurements were carried out at three bulk densities, which were obtained by settling the sample on a wooden bench. The bulk density range depends on the kernel moisture content, size and surface characteristics. Detailed measurement procedures can be found in a previous publication (Trabelsi & Nelson, 2003).

[1] Mention of company or trade names is for purpose of description only and does not imply endorsement by the US Department of Agriculture.

2.3. Computation of the dielectric properties

The dielectric properties of shelled peanuts are computed from the measurement of the modulus and phase of S_{21} under the following assumptions:

1. The material is a low-loss material, $\varepsilon'' \ll \varepsilon'$.
2. The wave retains its planar nature and original polarization after propagating through the layer of material.
3. There are no multiple reflections within the sample.

The dielectric constant and dielectric loss factor are computed as follows:

$$\varepsilon' = \left[1 + \frac{\Delta\phi}{360d}\frac{c}{f}\right]^2 \tag{3}$$

$$\varepsilon'' = \frac{\Delta A}{8.686\pi d}\frac{c}{f}\sqrt{\varepsilon'} \tag{4}$$

where c is the speed of light in m/s, f is the frequency in Hz, d the thickness of the layer of material in meters, ΔA is the attenuation in decibels, and $\Delta\phi$ is the phase shift in degrees. From all the data collected, only those fulfilling the conditions set forth above are reported. The attenuation and phase shift are calculated from the modulus and phase of S_{21} as follows:

$$\Delta A = 20 \cdot \log|S_{21}| \tag{5}$$

$$\Delta\phi = \varphi - 2\pi \cdot n \tag{6}$$

where n is an integer to be determined. With a vector network analyzer, φ can only be measured between −180° and +180°. An ambiguity in the phase occurs when the thickness d of the layer is greater than the wavelength in the material. Methods to resolve the phase ambiguity were proposed previously (Musil & Zacek, 1986; Trabelsi, Kraszewski, & Nelson, 2000). Both ΔA and $\Delta\phi$ are taken as positive numbers.

3. Dielectric-based methods for determining bulk density and moisture content

3.1. Direct use of dielectric properties for bulk density and moisture content determination

Dielectric properties can be used directly to determine bulk density and moisture content in shelled peanuts. Figs. 2 and 3 show variations of the dielectric properties

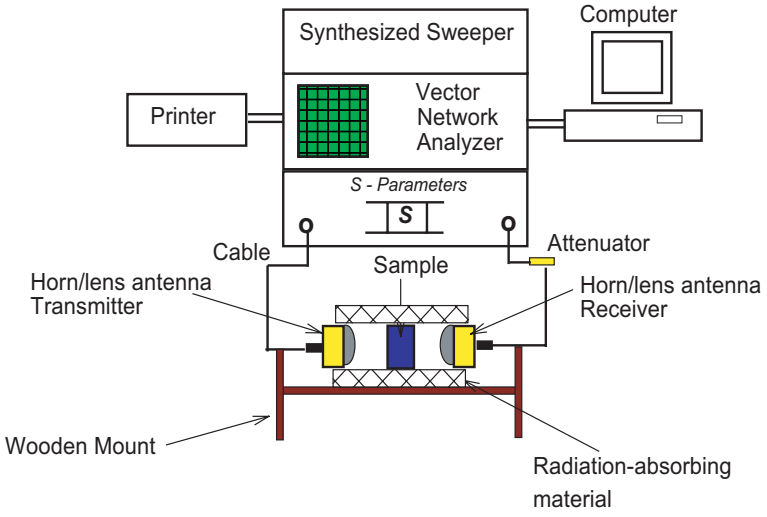

Fig. 1. Free-space measurement setup.

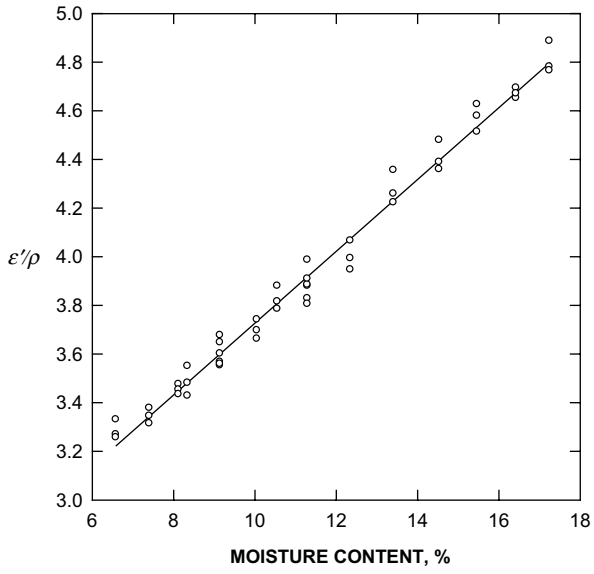

Fig. 2. Dielectric constant of shelled peanuts divided by bulk density as a function of moisture content at 10 GHz and 24 °C.

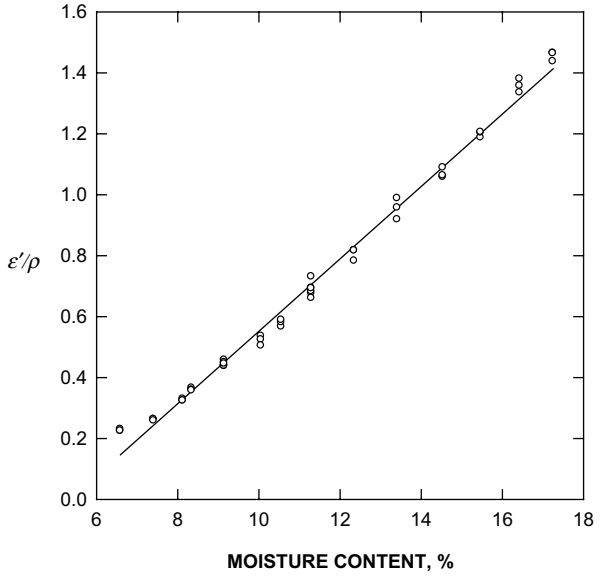

Fig. 3. Dielectric loss factor of shelled peanuts divided by bulk density as a function of moisture content at 10 GHz and 24 °C.

of shelled peanuts, divided by bulk density, with moisture content. The dielectric properties were divided by bulk density to minimize the scatter of data at each moisture level, which is mainly related to changes in bulk density. Both ε'/ρ and ε''/ρ increase linearly with moisture content for each material. Therefore, they can be fitted by linear regressions of the form:

$$\frac{\varepsilon'}{\rho} = aM + b \tag{7}$$

$$\frac{\varepsilon''}{\rho} = cM + d \tag{8}$$

Regression coefficients and coefficients of determination are given in Table 1 at several frequencies. The high coefficients of determination indicate the high correlation between the dielectric properties divided by bulk density and moisture content. The system of Eqs. (7) and (8) allows the simultaneous determination of bulk density and moisture content from measurements of the dielectric properties at a given frequency and temperature. Solving (7) and (8) for ρ and M:

$$\rho = \frac{c\varepsilon' - a\varepsilon''}{bc - ad} \tag{9}$$

$$M = \frac{d\varepsilon' - b\varepsilon''}{a\varepsilon'' - c\varepsilon'} \tag{10}$$

Table 1
Regression statistics corresponding to Eqs. (7)–(10) and the SEC for bulk density and moisture content determination for shelled peanut at different frequencies and 24 °C

Statistics	7 GHz	8 GHz	9 GHz	10 GHz	11 GHz	12 GHz
a	0.178	0.167	0.157	0.147	0.141	0.135
b	2.011	2.104	2.168	2.250	2.294	2.340
c	0.120	0.121	0.121	0.118	0.120	0.124
d	−0.683	−0.688	−0.680	−0.637	−0.643	−0.665
$r^2_{\varepsilon'}$	0.993	0.991	0.989	0.986	0.983	0.980
$r^2_{\varepsilon''}$	0.991	0.991	0.994	0.992	0.993	0.992
SEC_ρ (g/cm^3)	0.014	0.014	0.014	0.014	0.014	0.013
SEC_M (%)	0.42	0.39	0.37	0.40	0.37	0.35

Eqs. (9) and (10) are bulk density and moisture content calibration equations. To evaluate their performance in predicting bulk density and moisture content from complex permittivity measurements, the standard error of calibration (SEC) was calculated. The SEC is defined as:

$$\mathrm{SEC} = \sqrt{\frac{1}{l-p-1}\sum_{i=1}^{l}(\Delta e_i)^2} \tag{11}$$

where l is the number of samples, p is the number of variables in the regression equation with which the calibration is performed, and Δe_i is the difference between the predicted value and that determined by a standard method for the i th sample. Values of the SEC for bulk density and moisture content determination are given in Table 1.

Table 1 indicates that the SEC for bulk density determination is the same at all frequencies. The SEC values for moisture content determination range from 0.35% to 0.42%.

It is also possible to determine calibration equations for the mass of water per unit volume m_w/V and the mass of dry matter per unit volume m_d/V from Eqs. (9) and (10).

$$\frac{m_w}{V} = \rho \cdot \frac{M}{100} = \frac{b\varepsilon'' - d\varepsilon'}{(bc-ad)100} \tag{12}$$

$$\frac{m_d}{V} = \frac{(100c+d)\varepsilon' - (100a+b)\varepsilon''}{bc-ad} \tag{13}$$

3.2. Use of complex-plane representation for bulk-density determination

The complex-plane representation (Argand diagram) of the dielectric properties, also known as a Cole-Cole plot, is often used to analyze the behavior of dielectric materials (Hasted, 1973). In Fig. 4 an example is shown at 10 GHz. Instead of plotting ε'' versus ε', the dielectric loss factor divided by bulk density is plotted against the dielectric constant divided by bulk density for samples of different moisture contents. In this representation, data collected at different moisture contents and bulk densities are aligned along the same straight line (Trabelsi, Kraszewski, & Nelson, 2001) with data corresponding to higher moisture contents at higher coordinates. The same trend was found at all other frequencies. The x-axis intercept represents the dielectric properties divided by bulk density for a sample of shelled peanuts with zero moisture content or that corresponding to a sample of any moisture content at the "freezing" temperature of bound water. The intercept can be determined by extrapolation or by performing measurements on samples with zero moisture content (Trabelsi et al., 1998). Also, it could be determined by bringing the sample temperature down to bound-water "freezing" temperature. The data shown in Fig. 4 can be fitted by a linear regression of the form:

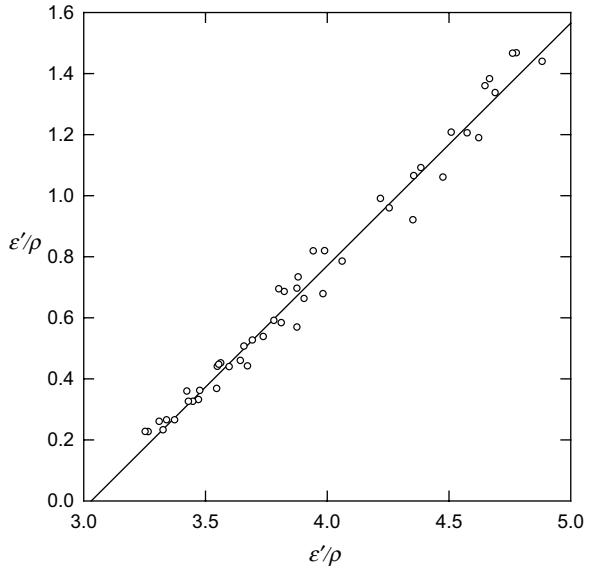

Fig. 4. Dielectric loss factor of shelled peanuts divided by bulk density versus dielectric constant of shelled peanuts divided by bulk density (Argand diagram) at 10 GHz and 24 °C.

$$\frac{\varepsilon''}{\rho} = a_f\left(\frac{\varepsilon'}{\rho} - k\right) \tag{14}$$

where a_f is the slope of the line and k is the x-axis intercept. Table 2 provides the regression coefficients and coefficients of determination at several frequencies. Table 2 indicates that the slope a_f increases with frequency and that the x-axis intercept is common to all frequencies. There exists a linear relationship between a_f and the frequency:

$$a_f = 0.045f + 0.351 \quad r^2 = 0.993 \tag{15}$$

where f is the frequency in GHz.

Table 2
Regression statistics corresponding to Eqs. (14)–(16) and the SEC for bulk density determination of shelled peanuts at different frequencies and 24 °C

Statistics	7 GHz	8 GHz	9 GHz	10 GHz	11 GHz	12 GHz
a_f	0.666	0.720	0.759	0.795	0.842	0.902
k	3.02	3.04	3.04	3.03	3.03	3.05
r^2	0.986	0.983	0.982	0.982	0.980	0.979
SEC_ρ (g/cm^3)	0.014	0.014	0.014	0.014	0.014	0.014

At a given frequency, bulk density can be determined from measurement of the dielectric properties directly from Eq. (14) as follows:

$$\rho = \frac{a_f \varepsilon' - \varepsilon''}{k a_f} \tag{16}$$

Eq. (16) indicates that bulk density can be determined without knowledge of moisture content and temperature. Values of SEC for bulk density determination with (16) are given in Table 2 at several frequencies. They are the same at all frequencies and equal to those determined in the previous section.

Fig. 5 shows that calculated values (calibration Eqs. (9) and (16)) are similar and remain close to the solid line representing the ideal relationship between calculated and gravimetrically determined values.

3.3. Use of permittivity-based density-independent functions for moisture content determination

Bulk density affects the complex permittivity in a way similar to that of water, leading to errors in moisture prediction from complex permittivity measurements if it is not accounted for (Trabelsi et al., 1999a). In many instances moisture content in granular materials has to be determined without knowledge of bulk density. In the mid seventies, the concept of sensing moisture content independent of bulk density changes was developed for this purpose (Kraszewski & Kulinski, 1976). Later, permittivity-based functions for moisture determination in hygroscopic granular materials independent of their bulk density changes were developed (Meyer & Schilz, 1980; Trabelsi et al., 1998). Two of the most effective functions (Kraszewski et al., 1998; Trabelsi & Nelson, 1998) were tested here for moisture determination in shelled peanuts. They are:

$$\psi_1 = \frac{\varepsilon''}{\varepsilon' - 1} \tag{17}$$

$$\psi_2 = \frac{\varepsilon''}{\varepsilon'(a_f \varepsilon' - \varepsilon'')} \tag{18}$$

ψ_1 was developed based on empirical findings (Kraszewski & Kulinski, 1976), which showed that the ratio of attenuation to phase was insensitive to bulk density changes over a given moisture content range. ψ_2 was defined based on the energy balance within the dielectric and findings from the complex-plane representation shown in the Section 3.2 (Trabelsi et al., 1998). It has been shown that ψ_2 is insensitive to bulk density changes and also to the material characteristics (size, shape and composition) (Trabelsi, Kraszewski, & Nelson, 1999b). As an example, Figs. 6 and 7 show variations of ψ_1 and ψ_2 with moisture content at 10 GHz and 24 °C. Both ψ_1 and ψ_2 increase linearly with moisture content.

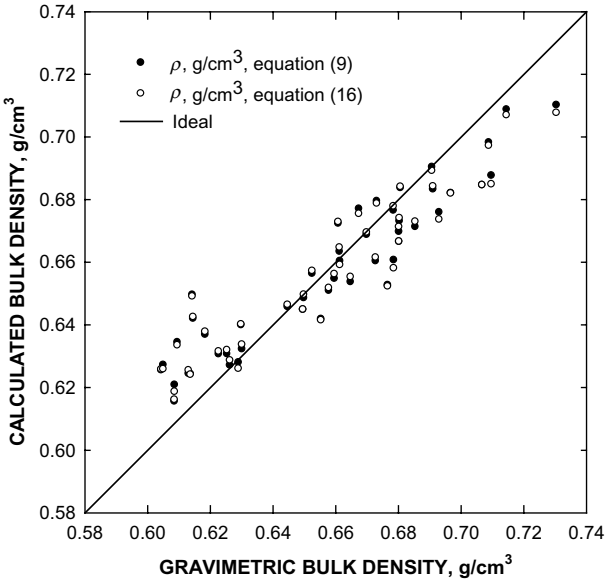

Fig. 5. Comparison of calculated (calibration Eqs. (9) and (16)) and gravimetric bulk densities.

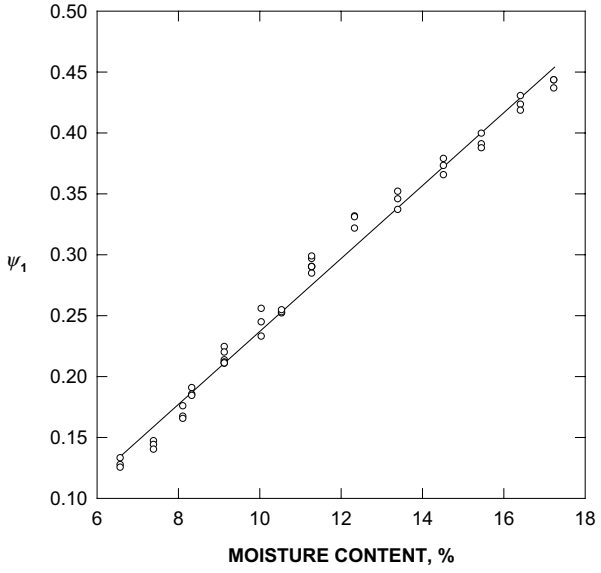

Fig. 6. Variation of density-independent permittivity function ψ_1 with moisture content at 10 GHz and 24 °C.

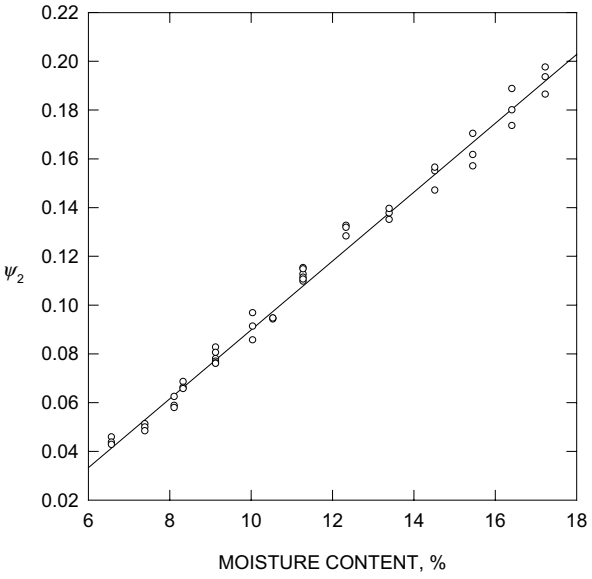

Fig. 7. Variation of density-independent permittivity function ψ_2 with moisture content at 10 GHz and 24 °C.

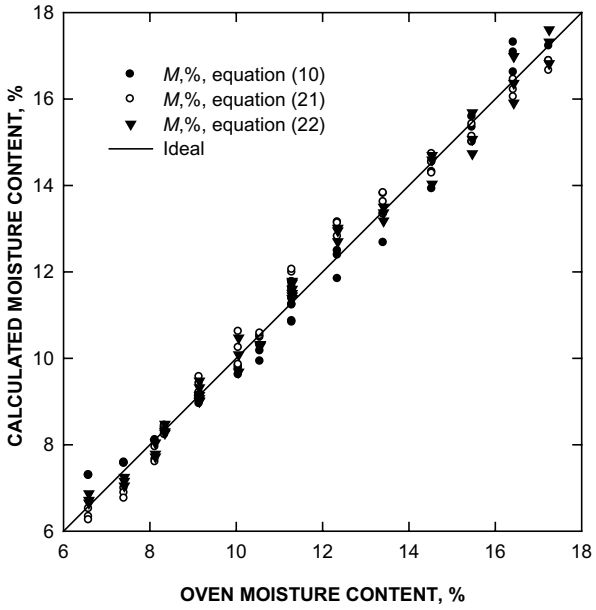

Fig. 8. Comparison of calculated (calibration Eqs. (10), (21) and (22) and oven moisture contents.

Thus, they can be fitted with linear regressions of the form:

$$\psi_1 = a_1 M + b_1 \tag{19}$$

$$\psi_2 = a_2 M + b_2 \tag{20}$$

Eqs. (19) and (20) provide explicit relationships between permittivity-based functions and moisture content. Regression constants for these equations and corresponding coefficients of determination are given in Table 3. The high values of the coefficients of determination indicate the high degree of correlation between permittivity-based calibration functions and moisture content in shelled peanuts.

Moisture calibration equations are determined from Eqs. (19) and (20) as follows:

$$M = \frac{\psi_1 - b_1}{a_1} \tag{21}$$

Table 3
Regression statistics corresponding to moisture calibration Eqs. (21) and (22) and the SEC for moisture content determination in shelled peanuts at different frequencies and 24 °C

Statistics	7 GHz	8 GHz	9 GHz	10 GHz	11 GHz	12 GHz
a_1	0.027	0.029	0.029	0.030	0.031	0.033
b_1	−0.057	−0.065	−0.056	−0.062	−0.068	−0.079
$r^2_{\psi_1}$	0.984	0.986	0.985	0.985	0.985	0.984
a_2	0.016	0.015	0.014	0.014	0.013	0.013
b_2	−0.061	−0.058	−0.053	−0.051	−0.051	−0.051
$r^2_{\psi_2}$	0.988	0.977	0.991	0.990	0.988	0.984
SECψ_1 (%)	0.36	0.34	0.38	0.39	0.40	0.41
SECψ_2 (%)	0.31	0.28	0.30	0.32	0.36	0.41

$$M = \frac{\psi_2 - b_2}{a_2} \tag{22}$$

The SEC values corresponding to moisture calibration Eqs. (21) and (22) are given in Table 3. In general, these values are similar to those determined with the first method (Section 3.1) with ψ_2 providing better accuracy.

In Fig. 8, calculated values of moisture content with calibration Eqs. (10), (21) and (22) are compared to those determined by oven drying. All three equations provided similar values, which are close to the solid line representing the ideal relationship between calculated and measured moisture contents.

4. Discussion and conclusions

Three dielectric-based methods were discussed for bulk density and moisture content determination in shelled peanuts. In total, two independent bulk density calibration equations and two independent moisture content calibration equations were obtained. Evaluation of performance of each calibration equation through calculation of the corresponding standard error of calibration at several microwave frequencies shows that bulk density can be determined with the same accuracy, about 1.7% relative error, with either method. However, for moisture content determination, density-independent permittivity functions, particularly ψ_2, performed slightly better than the direct use of the dielectric properties.

The fact that these methods use the complex permittivity to determine physical characteristics of shelled

peanuts, makes them applicable regardless of the measurement technique employed to measure the complex permittivity. This provides flexibility in the choice of the proper technique for a given application. The methods proposed in this paper constitute the basis for developing calibration algorithms that can be used separately or in combination for nondestructive characterization of shelled peanuts and other moist granular materials. Another advantage of these methods is that they require measurements of the complex permittivity at a single frequency for the simultaneous, instantaneous determination of two physical entities (moisture content and bulk density), which in practice translates into simplifying the sensor design and consequently a reduction in price. The choice of operating frequency is a compromise considering several design and cost factors, which include desired accuracy, sample size, available dynamic range, and cost of microwave components. Different configurations can be considered in developing a microwave sensor for shelled peanut characterization. It could be either a hand-held device for routine measurements or an on-line system suitable for real-time monitoring of a given industrial process. Both sensor configurations can find widespread use at different processing stages for shelled peanuts. Robustness of the calibration methods presented in this paper and availability of inexpensive microwave components are incentives for the development of such sensors.

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